SITING CULTURE OPERATIONS FOR THE PACIFIC OYSTER CRASSOSTREA GIGAS

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PREFACE

Choosing a site for Pacific oyster culture is a multi-factor problem. Efficient production depends on the Economic Suitability of a site (factors related to site acquisition, operating and marketing) and Habitat Suitability (how well oysters can be expected to grow and survive). A model has been constructed to evaluate culture sites which is composed of these two parts.

The model is patterned after the widely recognized procedures used by the U.S. Fish and Wildlife Service to evaluate habitat requirements for terrestrial and aquatic species. The ability of the model to predict growth and survival has recently been field-tested and found to usefully reflect growth and survial of Pacific oysters. The methods and results from this study are included in the report to help the user understand the basis of the model.

The report will help prospective growers select culture sites based on specific production strategies and provide a further understanding of how environmental variables influence production in existing farm operations. The criteria and methodology of siting will allow coastal planners and resource managers to quantitatively rate areas for oyster culture, thereby providing a basis for avoiding or mitigating coastal use conflicts with the industries such as fishing, forestry, mining, petroleum and tourism.

The report discusses in detail the economic and biological factors that influence choice of a site. The discussion alone may suffice as a guide to siting an operation; however, where a more objective decision is desired, the model user is guided through an exercise that:

1. rates, on a scale from poor (0) to optimal (1.0), each economic or biological factor under consideration, and
2. relates the values of these factors in relatively simple equations, and
3. gives an indexed value of the culture potential of an area for the:
    a) economic aspects,
    b) the biological aspects, and
    c) the general culture suitability of a site.

A detailed appendix describes how to obtain data on these factors. For example, water transparency and colour can be used to estimate food supply as many growers can not chemically analyse water supplies for food content.

We hope this booklet is useful to potential and experienced oyster culturists and coastal resource managers.

William Roland
James Brown

SUMMARY

Selection of a good site for the culture of the Pacific oyster is critical for a successful operation. In this report we present a model by which a site is selected through the use of a Culture Suitability Index (CSI). The CSI has two components: the Economic Suitability Index (ESI) which includes economic and management factors; and the Habitat Suitability Index (HSI)) which refers to biological and oceanographic variables affecting oyster growth and survival. The HSI was field-tested at 10 sites in British Columbia and was significantly correlated to oyster growth and production. The ESI is discussed but was not field tested. This part of the model is best used as a guideline because, in contrast to problems with water quality, management practices can significantly determine the severity of and solution to most siting problems related to economic variables. Use of the CSI model and the measurement of economic and biophysical variables are discussed and detailed with examples.

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INTRODUCTION

The choice of a site for culture of the Pacific oyster, Crassostrea gigas Thunberg, is a multi-factor problem. Efficient production depends on the Economic Suitability of a site (factors related to site acquisition, operating and marketing) and Habitat Suitability (how well oysters can be expected to grow and survive). Herein we present a model to evaluate culture sites which is composed of these two parts. The framework of the model is patterned after the U.S. Fish and Wildlife Service's, Habitat Evaluation Procedures (U.S.F.W.S. 1980) which have been used to model habitat requirements of numerous terrestrial and aquatic organisms (Schamberger and Krohn 1982), including wild populations of American oysters, C. virginia, (Cake 1983) and the little neck clam, Protothaca staminea, (Rodnick and Li 1983). It is a unique model for C. gigas because the assumptions used to rate the biological capability of sites were field-tested (Brown and Hartwick In Press a). Results and interpretations from this study are presented to give the basis for our estimate of the model's precision. Recommendations are given for seasonal use of the model and methodology for measurement of variables is presented.

This booklet can help prospective growers select culture sites based on specific production strategies and provide a further understanding of how environmental variables influence production in existing farm operations. The criteria and methodology of siting can allow coastal planners and resource managers to quantitatively rate areas for oyster culture, thereby providing a basis for avoiding or mitigating coastal use conflicts with industries such as fishing, forestry, mining, petroleum and tourism.

1. ECONOMIC SUITABILITY MODEL

Nine factors were identified that, from a management viewpoint, have a major impact on the suitability of a site for oyster culture. For each variable a corresponding graph was drawn (Figure 1). Quantitative values were not given for these factors, nor could this model be satisfactorily tested, because management strategies can significantly determine the severity of and solution to most siting problems related to economic variables.

Multiple variable interactions are accounted for in three Economic Indices (EI) which are Human Activity, Accessibility, and Paralytic Shellfish Poisoning. The overall Economic Suitability Index (ESI) is derived from a composite of the EI values (Table 1). In the model, the equations use geometric averages of Economic Index Values rather than more familiar arithmetic averages. The use of this type of average is important because in practice high values of several variables do not compensate for low values of others, as much as arithmetic averages would suggest.

1.1 EI (Human Activities)

Theft (E_1) can be a serious problem for beach culture in certain areas. The magnitude of this risk is not certain as few poachers are convicted and, except where the amount of theft is large, growers seldom have an adequate enough inventory of their stock to detect theft.

Recreational conflicts (E_2) can result from having off-bottom culture located in an area often used as a boat anchorage, or from having a bottom culture tenure in an area of high recreational use where tourists may poach oysters or destroy seed-stock by walking on a beach.

Clam harvesting (E_3) is a serious problem in many areas suitable for bottom culture. The problem is inherent because clams and oysters grow well on the same substrate, that is, a firm gravel-sand-mud mixture. Clam harvesting involves digging and raking which can bury or mechanically damage seed and older stock. The guidance for oyster culturists at the present time is to avoid culture in harvested areas, but the proponent is advised to check the status of the problem since policy is continually evolving.

Interference with navigation (E_4) can, at the discretion of the Federal government, prohibit or add to the cost of culture. Any beach or off-bottom structure must be properly marked and the type, and, hence the expense of marking (ranging from colored floats to lights) increases with maritime activity. Structures are not allowed to prevent access to private property and, at the discretion of the Provincial government, may not be permitted where access to Crown land is prohibited. Restriction of anchorage or passage, that is not easily rerouted, may not be allowed. Even if approved, frequent boating traffic creates wake and increases risk of collision with structures.

Pollution (E_5) can make an area unsuitable for culture. Fecal contamination may be a perennial problem around inhabited areas or seasonal in areas which have summer recreational use from cottages or anchorages and may also result from freshwater run-off where livestock graze (Turner and Morris 1981). Toxic pollution from sources such as pulp mills, chemical industries and mines that discharge waste into water may prevent culture. Log handling may increase silt and debris concentrations in the water. Organo-tin compounds used in anti-fouling coatings on vessels and occasionally on salmon farm net pens can cause abnormal growth of C. gigas (Waldock and Thain 1983). We cannot present guidelines for modelling the effects of a pollution source, because it is a complex process involving water currents, dilution, discharge patterns and volumes, and toxicity. Where a problem is perceived we recommend choosing a different site, or at least 2-3 years test-culture and regular monitoring of water quality.

Riparian rights (E_6) refers to the rights of owners of lands up-shore from a site to unimpeded beach access and egress, thus the owners must give approval for any structures placed intertidally, or off-bottom, which may restrict beach access and

egress (as legally defined, see B.C. Lands, Parks, and Housing 1984). Problems obtaining consent likely increase with the number of owners affected.

1.2 EI (Accessibility)

Access to the site and to certain facilities may be critical with certain types of culture or marketing strategies.

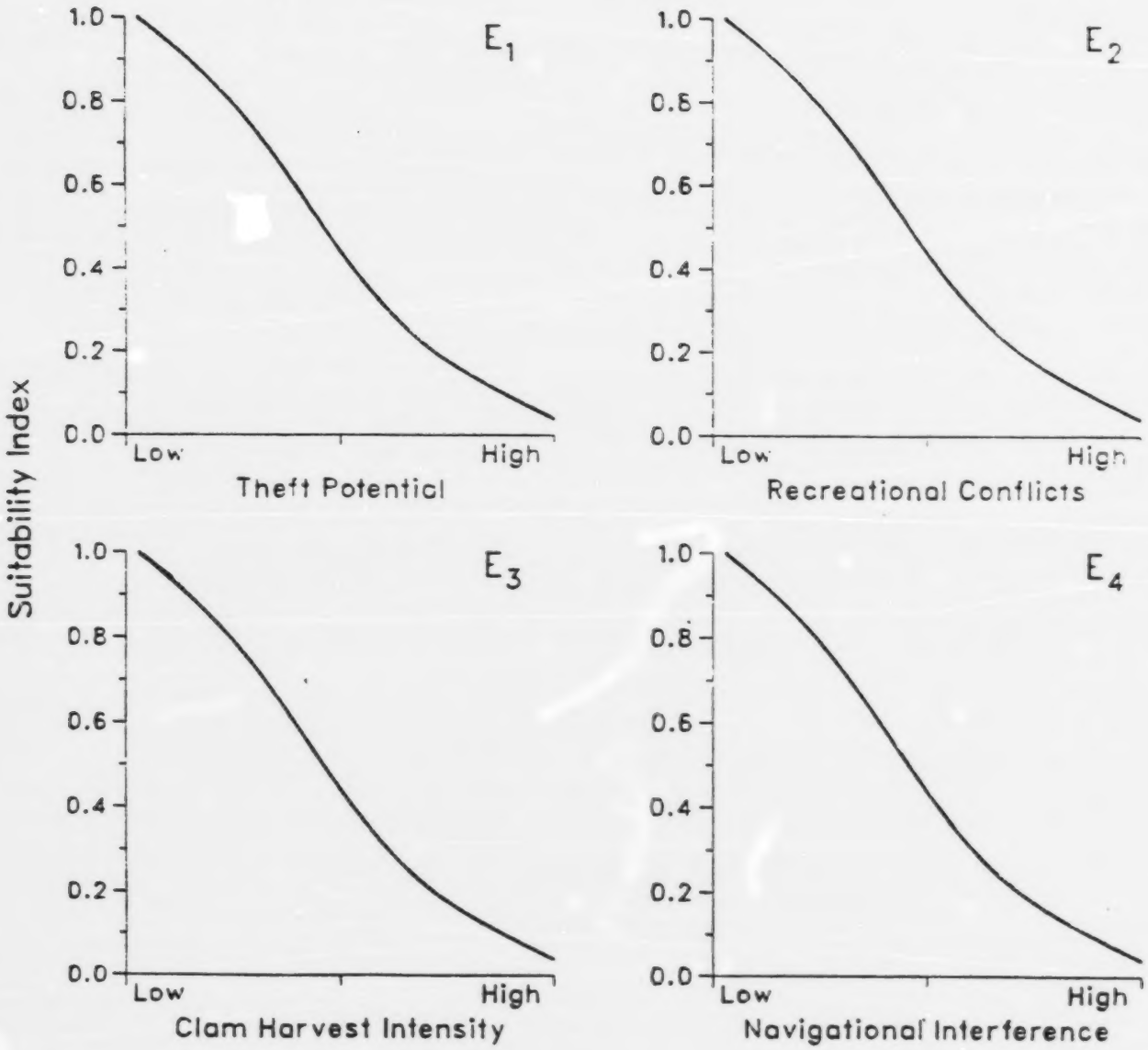
Distance (E_7) of the site from the base work-place, power and processing facilities can greatly affect the cost or type of culture technology used. Employees must be shuttled to and from work sites and the product brought to processing facilities, possibly making easy road and boat access critical, particularly for an operation with frequent market commitments. Operations producing or setting larvae may require power, fresh water and sea water.

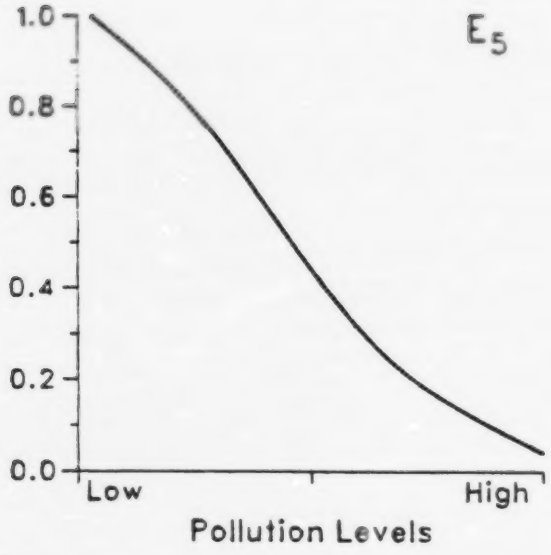
Surveillance (E_8) of a site can discourage theft and commercial clam digging. It can facilitate timely maintenance of gear and monitoring of stock growth and survival, and permit regular control of fouling and predation.

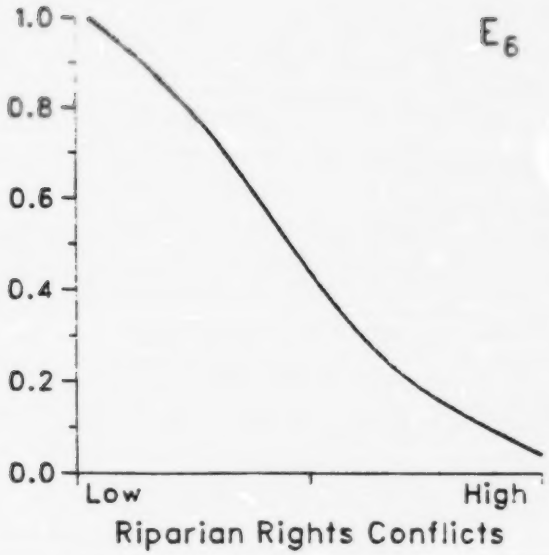
1.3 EI (Paralytic Shellfish Poisoning)

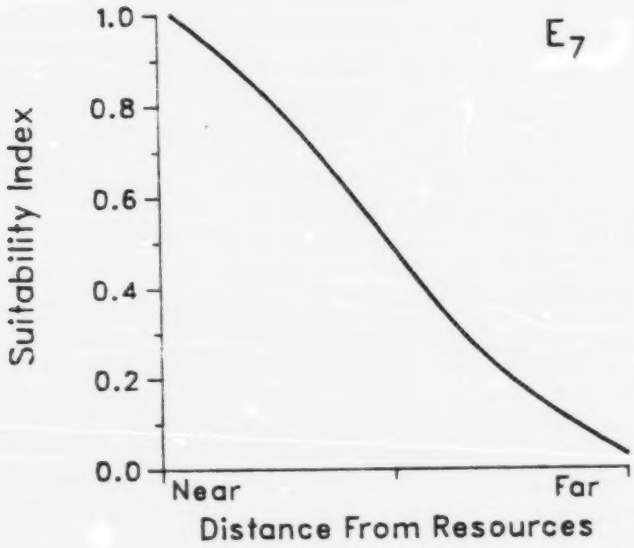
A natural environmental factor not seriously affecting growth and survival but which greatly impedes marketing is paralytic shellfish poisoning (E_9) (PSP or red tide). Many good culture areas are closed infrequently or for only one or two months a year. Unfortunately certain large areas of the B.C. coast are always closed to shellfish harvesting, necessitating the cumbersome process of monitoring oysters and possible depuration before processing.

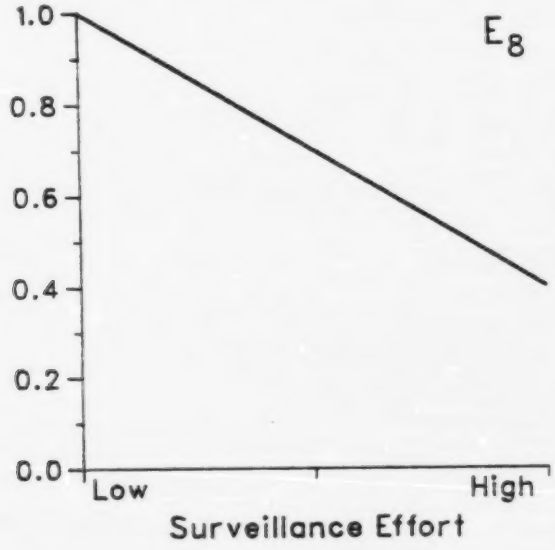
Figure 1. Suitability index graphs for economic variables where: E_1 = Theft potential; E_2 = Recreational Conflicts; E_3 = Clam Harvest Intensity; E_4 = Navigational interference; E_5 = Pollution effects; E_6 = Conflicts with riparian rights; E_7 = Distance to markets and shore-based resources; E_8 = Effort required for adequate surveillance; and E_9 = disruption due to PSP closures.




E_5
1.0
0.8
0.6
0.4
0.2
0.0
Low
High
Pollution Levels


E_6
1.0
0.8
0.6
0.4
0.2
0.0
Low
High
Riparian Rights Conflicts


Suitability Index
E_7
1.0
0.8
0.6
0.4
0.2
0.0
Near
Far
Distance From Resources


E_8
1.0
0.8
0.6
0.4
0.2
0.0
Low
High
Surveillance Effort

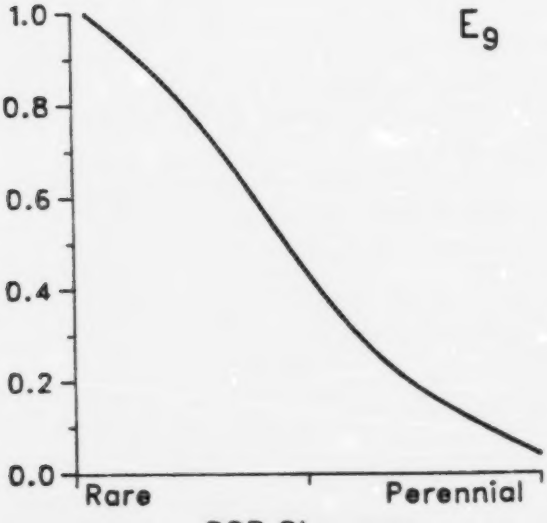

E_9
1.0
0.8
0.6
0.4
0.2
0.0
Rare
Perennial

Table 1: Economic Index equations and worksheet. See Appendix B for example of use.

Variable	Index Value	Comments
E_1 (Theft)	_____	
E_2 (Recreational Conflicts)	_____	
E_3 (Clam Harvesting)	_____	
E_4 (Navigation Conflicts)	_____	
E_5 (Pollution)	_____	
E_6 (Riparian Rights)	_____	
E_7 (Distance)	_____	
E_8 (Surveillance)	_____	
E_9 (PSP)	_____	

Steps to Calculate Economic Suitability Index (ESI)

1. EI (Human Activity) =

   $[(E_1 \times E_2 \times E_3)^{0.33} \times (E_4 \times E_5 \times E_6)^{0.33}]^{0.50}$

   $[(\_\_ \times \_\_ \times \_\_)^{0.33} \times (\_\_ \times \_\_ \times \_\_)^{0.33}]^{0.50} =$ _____* for on-bottom culture or

   $[(E_1 \times E_2)^{0.50} \times (E_4 \times E_5 \times E_6)^{0.33}]^{0.50}$

   $[(\_\_ \times \_\_)^{0.50} \times (\_\_ \times \_\_ \times \_\_)^{0.33}]^{0.50} =$ _____* for off-bottom culture

2. EI (Access) = $(E_7 \times E_8)^{0.50}$

   $= (\_\_ \times \_\_)^{0.50} =$ _____*

3. EI (PSP) = E_9 = _____

4. Economic Suitability Index = ESI =

[EI (Human Activity) x EI (Access) x EI(PSP)]$^{0.33}$ =

[_____ x _____ x _____]$^{0.33}$ = ____*

*To solve an equation such as $(E_1 \times E_2 \times E_3)^{0.33}$, simply multiply the three values together and take the 0.33 power or cube root of the product; for example:

$(.4 \times .7 \times .6)^{0.33} = (0.168)^{0.33} = \underline{0.56}$

The product of the three numbers (0.168) taken to the 0.33 power (0.56) can be read from Figure 9 in Appendix B.

2. HABITAT SUITABILITY MODEL

Twelve variables are identified that influence oyster growth and survival. Conditions affecting reproduction were not considered because seeding of an oyster lease is under control of the grower. For each variable, a corresponding suitability index graph was drawn (Figure 2). When quantitative values were not available for a particular variable, histograms were used to derive SI values from qualitative information. Multiple variable interactions are accounted for by three Life Requisite Suitability Indices (LRSI) which are Growth, Survival, and Water Chemistry and the overall Habitat Suitability Index (HSI) is derived from a composite of the LRSI values (see Table 2). Variable interactions are accounted for through calculations of geometric averages in the indices instead of arithmetic averages since compensatory relationships between various values of variables were perceived to be weak (U.S.F.W.S. 1981). A poor value of one variable should not be compensated for by a high value of another variable; thus geometric averages are used because they are lower (more conservative) than more familiar arithmetic averages.

2.1 LRSI (Growth)

The first life requisite, LRSI (Growth), encompasses those factors in which changes elicit an incremental growth response. For both on-bottom and off-bottom culture, a composite capability index for food and temperature was derived.

Water temperature (V_1) influences ventilation rate, hence assimilation efficiency in bivalves (Bernard 1983). High water temperatures during periods of low food availability can have a detrimental effect on growth (Malouf and Breese 1977). Growth is greatly curtailed or non-existent below temperatures between 8 - 10°C (Quayle 1969).

The functional relationship of available food (V_2) to biological capability follows that described by Tenore and Dunstan (1973), Malouf and Breese (1977) and Bernard (1983) for food concentration and the ability of oysters to use the food at various concentrations. The range of particulate organic matter (POM) concentrations covered by the SI graph corresponds to particle concentrations observed in the Strait of Georgia (Harrison et. al. 1983) and coastal inlets (Stockner and Cliff 1975, Brown 1986). The SI graph for available food is expressed in terms of concentration of either total particulate organic matter (mg/l) or phytoplankton pigments (µg/l chlorophyll a).

Substrate (V_3) composition is of major importance to bottom culture of oysters. It may also be important to off-bottom culture if the substrate is contributing significant levels of suspended sediments to the water column. Slower growth rates

and higher mortalities can occur in substrates laden with loose silt (Albrecht and Clayton 1983). Oysters grown on softer substrates develop elongated shells which result in a smaller volume of oyster meat (Gunter 1938, Quayle 1969). A hard bottom will encourage growth of better shaped oysters with a higher condition index. A rock or gravel bottom may have excessive wave-action associated with it which can damage the oyster or require the building of a breakwater to temper wave action, therefore, a bottom of gravel with firm sand or mud is best (Quayle 1969).

Growth decreases with increasing tidal level and duration of intertidal exposure (V_4) (Woelke 1959a). Exposure times of less than 10% to air appear to have little effect upon the growth of oysters (Spencer et al. 1978). Over a range of exposure periods of 10-30% a marked reduction in growth rate occurs. Since the effect on meat and shell growth is similar, a condition index based on how well the meat is filling the shell cavity, typically remains constant irrespective of tidal exposure.

The optimum location for good growth would be a tidal level where the oyster is almost continously submerged, but in practice, the grower must consider a trade off between growth and survival. The highest survival rate occurs at the 1.5-2.5 m level because of the relative absence of predators and competitors (fouling organisms). Quayle (1969) recommends initially planting small seed oysters at the 1.5-2.5 m tidal levels, until they reach a less susceptable size, at which time they can be redistributed at lower tidal levels to maximize growth. The grower must consider the area of useable beach within these tide heights of 0.6 m to 2.5 m (growing oysters below 0.6 m meters on a beach is not recommended because the amount of time that the tide is out is very limited, making work with the stock difficult).

For off-bottom culture, LRSI (Growth) was equal to the geometric mean of water temperature and available food. LRSI (Growth) for on-bottom culture is the least suitable of:

1. the temperature-food mean,
2. substrate composition, or
3. intertidal exposure

2.2 LRSI (Survival)

The second life requisite, LRSI (Survival), concerns variables which have negative effects on growth and survival. Suspended sediments (V_5), disease (V_7), fouling organisms (V_8), and predators (V_9) were all considered to be optimal when absent or present at very low levels. Disease can restrict oyster culture

although the frequency and intensity of out-breaks has been low in British Columbia waters in comparison to the Atlantic oyster industry (Quayle 1961, 1969, Bourne 1979, Sinderman 1984). High densities of predators (primarily the seastars, Pisaster ochraceus and Pycnopodia helianthoides) and fouling organisms (particularly, the mussel Mytilis edulis and barnacle, Balanus glandula) require more culture maintenance, thereby increasing labour costs (Woelke 1959b, Quayle 1969, 1971, Humphries 1976, Michael and Chew 1976). Suspended sediment concentrations in excess of 75.0 mg/l could be harmful to the oyster (Loosanoff and Tommers 1948, Bernard 1983) although such levels have not been reported in British Columbia coastal fjords (Thomson 1981, Harrison et al. 1983).

Water movement (V_6) at tidal flow velocities can benefit growth through the circulation of food particles and the dissipation of waste products (Westley 1965, Walne 1972, Frechette and Bourget 1985). Stagnant water or heavy wave action are extreme conditions which have negative effects on oyster culture (Quayle 1969), thus water movement and suspended sediments are not included in the model unless their respective SI values are less than 0.70.

2.3 LRSI (Water Chemistry)

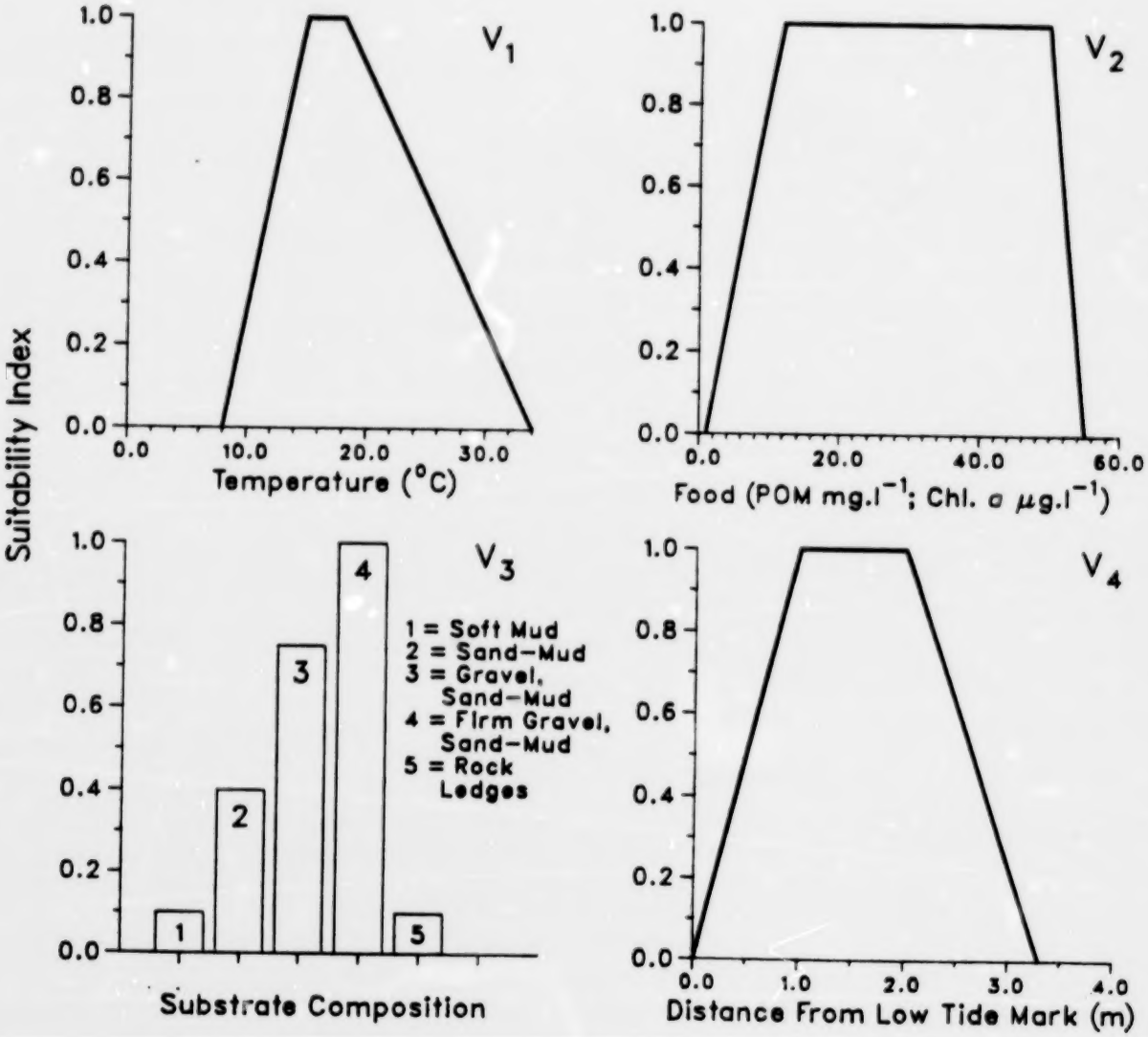
The third life requisite includes the water chemistry variables salinity (V_{10}), dissolved oxygen (V_{11}) and pH (V_{12}) which do not affect growth and survival as long as the conditions of the variables fall within the optimal zone of the oyster.

Salinity can vary greatly with season and location in British Columbia waters (Thomson 1981, Harrison et al. 1983). Due to seasonal influxes of freshwater, some areas have prolonged periods of salinity readings below 20 ppt which would be stressful to oysters (Hopkins 1936, Quayle 1969, King 1977, Bernard 1983).

Dissolved oxygen and pH are not limiting to oysters in coastal embayments which have some water circulation (Westley 1965, Kuwatani and Nishii 1969, Davis 1975). In B.C. both variables fluctuate seasonally with phytoplankton abundance (Parsons and Takahashi 1973) but remain within the tolerance zone of the oyster. It is conceivable, however, that intolerable conditions of these variables could exist as the result of poor water circulation or pollution (Menzel 1979).

If LRSI (Water Chemistry) is not limiting ($\geq$ 0.70), then the overall HSI is the geometric mean of LRSI (Growth) and LRSI (Survival) (see Table 2). If LRSI (Water Chemistry) is limiting then oyster growth is assumed to be reduced. The geometric mean of LRSI (Growth) and LRSI (Water Chemistry) is initially calculated then the geometric mean of this value and LRSI (Survival) is determined to arrive at the overall Habitat Suitability Index (HSI) rating.

Figure 2. Suitability index graphs for habitat variables where: V_1 = Water temperature; V_2 = Available food; V_3 = Substrate composition; V_4 = Intertidal exposure; V_5 = Suspended sediments; V_6 = Water movement; V_7 = Disease; V_8 = Fouling organisms; V_9 = Predators; V_{10} = Salinity; V_{11} = Dissolved oxygen; and V_{12} = pH.



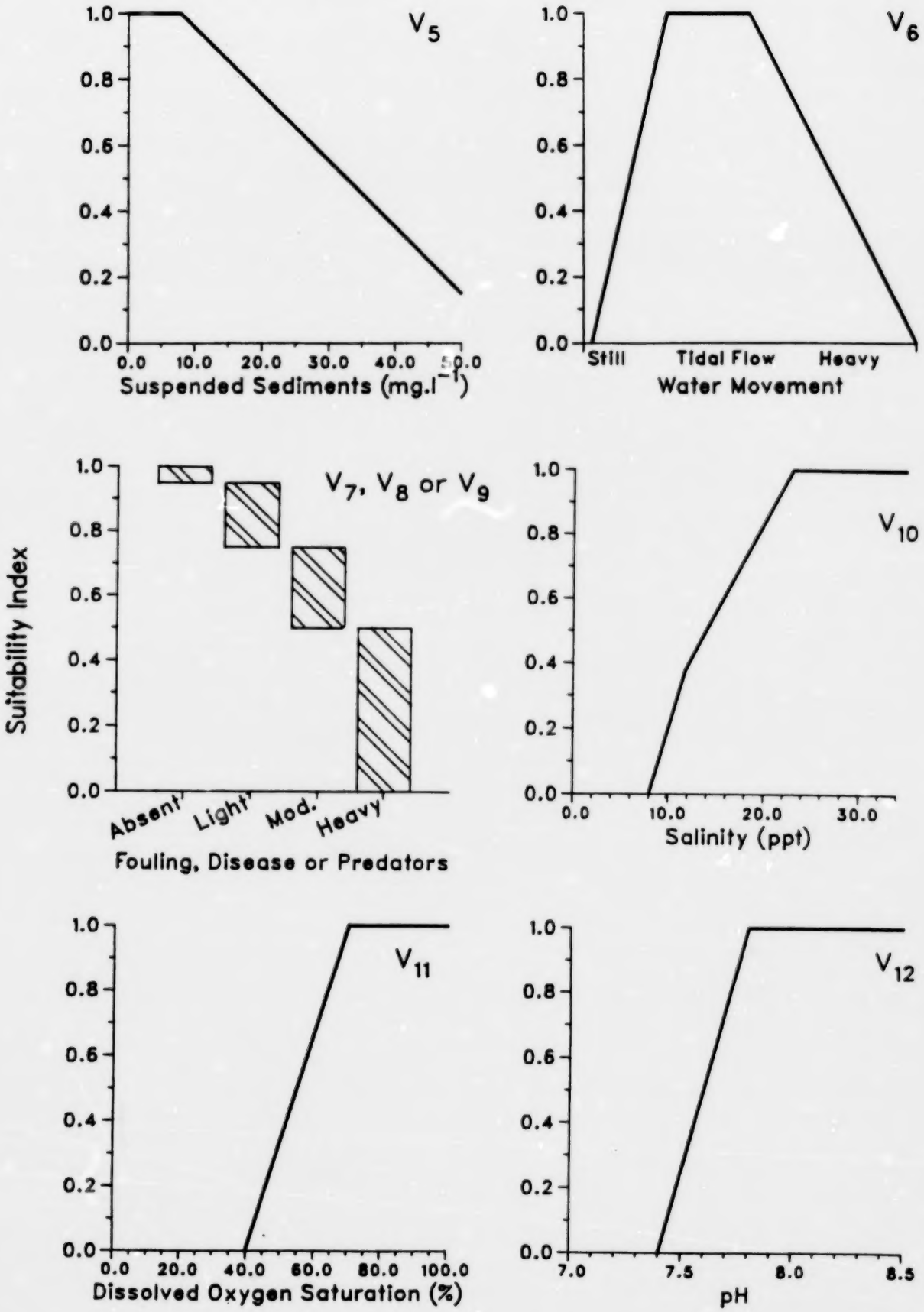

V_5
1.0
0.8
0.6
0.4
0.2
0.0
0.0 10.0 20.0 30.0 40.0 50.0
Suspended Sediments (mg.l^{-1})
V_6
Still
Tidal Flow
Heavy
Water Movement
Suitability Index
V_7, V_8 or V_9
Absent
Light
Mod.
Heavy
Fouling, Disease or Predators
V_{10}
0.0 10.0 20.0 30.0
Salinity (ppt)
V_{11}
0.0 20.0 40.0 60.0 80.0 100.0
Dissolved Oxygen Saturation (%)
V_{12}
7.0 7.5 8.0 8.5
pH

Table 2. Life Requisite Suitability Index (LRSI) and Habitat Suitability Index (HSI) worksheet and equations. See Appendix B for example of use.

Variable	Index Value	Data and Comments
V_1 (Temperature)	_____	
V_2 (Available Food)	_____	
V_3 (Substrate)	_____	
V_4 (Intertidal Exposure)	_____	
V_5 (Suspended Sediments)	_____	
V_6 (Water Movement)	_____	
V_7 (Disease)	_____	
V_8 (Fouling Organisms)	_____	
V_9 (Predators)	_____	
V_{10} (Salinity)	_____	
V_{11} (Oxygen)	_____	
V_{12} (pH)	_____	

Steps to Calculate Habitat Suitability Index (HSI)

1. LRSI (Growth) = $(V_1 \times V_2)^{0.50}$ = (__ x __)$^{0.50}$ = ____*

   *For on-bottom culture only, LRSI (Growth) = the lesser of $(V_1 \times V_2)^{0.50}$ or V_3, or V_4

2. LRSI (Survival) = the lesser of V_5, V_6, V_7, V_8, or V_9 = ____. This is because all are considered to affect survival in a major way and poor values of one or more cannot be compensated in any way by high values of other variables.

3. LRSI (Water chemistry) = the lesser of V_{10}, V_{11}, or V_{12} = ____. Again, a poor value for one variable is detrimental to culture.

4. Habitat Suitability Index = HSI =

   [LRSI (Growth) x LRSI (Survival)]$^{0.50}$ = ____*, if LRSI (Water Chemistry) is greater than or equal to 0.70. If it is less than 0.70 then the HSI = [[LRSI (Growth) x LRSI (Water Chemistry)]$^{0.50}$ x LRSI (Survival)]$^{0.50}$ = ____*

*Note: See Figure 9 (Appendix B) for values of numbers taken to the 0.50 power.

3. CULTURE SUITABILITY INDEX

The suitability of a site for culture of oysters is a function of the ESI and HSI values (Table 3). We generally recommend that oysters not be cultured if either index is less than 0.5 or if the Culture Suitability Index (CSI) is less than 0.5. The CSI is defined as :

$$CSI = (ESI \times HSI)^{0.50}$$

where ESI is the Economic Suitability Index value and HSI is the value for the Habitat Suitability Index.

TABLE 3 Culture Suitability Index equations and worksheet. See Appendix B for example of use.

Culture Suitability index = CSI =

$(ESI \times HSI)^{0.50} =$

$(\underline{\quad} \times \underline{\quad})^{0.50} = \underline{\quad}$*

Where ESI is the value for the overall Economic Suitability Index and HSI is the value for the overall Habitat Suitability Index.

*Note: See Figure 9 (appendix B) for values of numbers taken to the 0.50 power.

4. FIELD VALIDATION

The fundamental design of the validation study was to grow oysters subtidally in ten locations ranging from relatively good to poor conditions for oyster growth and survival. Data collected on environmental factors were used as inputs into the HSI model. The derived HSI ratings were then compared to oyster growth and production in order to evaluate the performance of the model (Brown 1986, Brown and Hartwick In Press a).

4.1 Methods

The sites, shown in Figure 3, were Lemmens Inlet (1 and 2), Saanich Inlet (1 m and 5 m), Departure Bay, Bowen Island, Keats Island, West Vancouver, Trevenen Bay and Okeover Inlet. Sites were monitored monthly from June 1984 to August 1985, except for January 1985.

At each site, two age-classes of cultchless oysters from the same seed-stock were used, and designated as Year 0 (20-30 mm shell height) and Year 1 (40-50 mm shell height). Approximately 170 oysters were spread evenly in a five tiered lantern net (30 cm diameter by x 1 m) to minimize any effect of density upon growth. All nets were attached to floating platforms and, except for Saanich 5 m, the tops of the nets remained at 1 m below the surface throughout a tidal cycle. The nets were cleaned or changed whenever the density of fouling organisms appeared to impede water circulation.

During each visit, shell heights of 20 randomly selected oysters from each age-class (4 from each tier of the net), were measured. Shell height is the distance from the end of the umbo to the most distant shell margin (Galtsoff 1964). The left or cupped valves of dead oysters from the entire net were removed, counted and their shell height measured.

From the monthly sample of 20 Year 1 oysters, 10 were randomly chosen for laboratory determination of dried meat weight (which was used in the calculation of secondary production). Body tissue was separated from the shell and weighed after drying the oyster meat at 60 °C to a constant weight (48-72 h).

Since initial sizes of oysters were similar among all sites at the beginning of the study, shell growth, for use in model validation, was calculated from the equation:

$$G = \frac{H_t - H_{t-1}}{D}$$

where G is daily increase in shell height (mm/day), H_t is shell height (mm) at the end of the study, H_{t-1} is the height (mm) at the beginning of the study and D is number of days between observations.

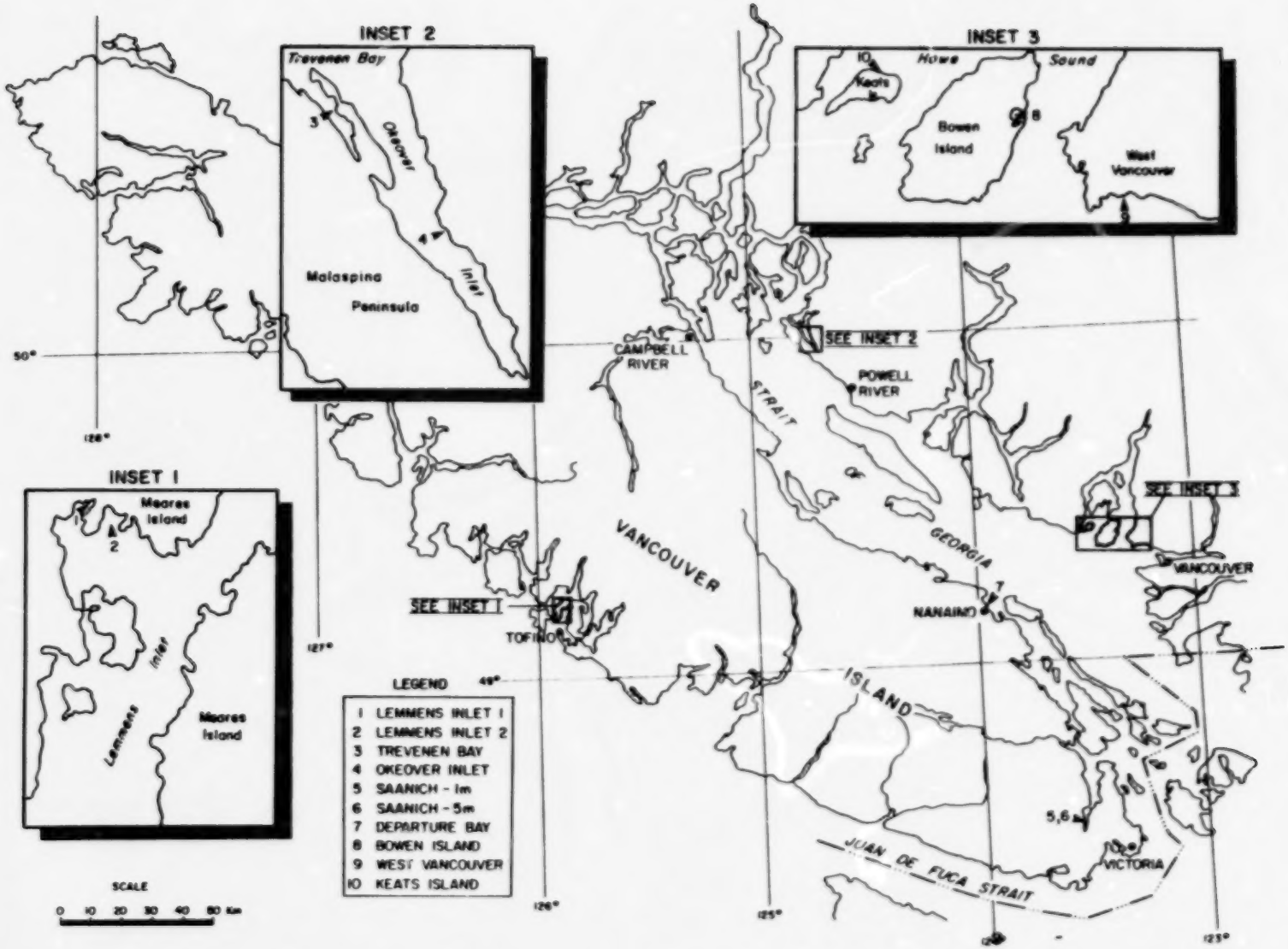


FIGURE 3. LOCATIONS OF STUDY SITES

Oyster production was calculated using the growth increment summation method of Rigler and Downing (1984) which takes into account both increases in biomass as a result of growth and decreases due to mortality. For Year 1 oysters, dry meat weight data were obtained from monthly samples. Dry meat weight of Year 0 oysters and body tissue losses due to mortality for both age-classes were determined from regression equations derived from the Year 1 oyster data. Total production was the summation of monthly incremental changes in dry meat weight of an initial population of 100 oysters divided by the number of days oysters were grown at a particular site.

Concurrent with each monthly site visit, environmental variables were measured. Sampling and analytical methodology are discussed in detail in Appendix 1. Briefly, duplicate or triplicate samples were taken of water temperature, salinity, phytoplankton biomass, total particulate matter (TPM), particulate organic matter (POM), particulate inorganic matter (PIM) or suspended sediments, pH and dissolved oxygen. Duplicate samples were collected the same day approximately 2-4 h apart. Whenever possible, a subsequent sample was taken within the next 24-48 h. Water samples were taken about 5 m up-current of the oyster nets at a depth equivalent to the mid-point of the nets.

Water temperature and salinity were measured using a YSI Model 33 S-C-T meter. Phytoplankton biomass was determined from the concentration of chlorophyll a pigments following the procedure of Strickland and Parsons (1982). For particulate matter analyses, a 0.5-1.0 l seawater sample was filtered through a pre-weighted glass fiber filter. TPM concentration (mg/l) was weight of residue on the filter after drying at 60°C for 12 h. POM was the weight loss after combustion at 450°C for 5 hours and PIM the weight of the remaining residue. Winkler titration was used to determine dissolved oxygen concentration. Fouling was assessed qualitatively from the densities of mussels (M. edulis) and barnacles (B. glandula).

Levels of pH were measured using a portable Beckman pH meter. This measurement was discontinued in September, however, pH levels below 7.0 which are stressful to the oyster were never recorded (Carriker 1959, Epifanio et al. 1975). Water flow was not evaluated since the proper instrumentation was not available. Predators were also excluded from the model evaluation since the oysters were protected in nets. None of the observed mortalities could be attributed to known disease agents.

Model assumptions regarding intertidal exposure and substrate compositon were not evaluated since on-bottom sites were excluded from the field study. The effects of these variables

upon oyster growth have been studied in depth previously (Gunter 1938, Quayle 1969, Spencer et al. 1978) thus the model assumptions derived from these works were considered to be realistic.

Regression analysis was used to statistically evaluate the relation of site-specific HSI ratings to oyster growth and production. A perfect correlation between HSI values and oyster growth or production would be a linear relationship. In this case, the coefficent of determination (r^2) would equal 1.0, that is, the HSI value would account for 100% of the measured variation in growth or production. If the model predictions were not correlated to oyster performance, points from a plot of HSI values versus growth would be randomly scattered on the graph with r^2 closer to 0.0. Probablity or 'p' levels less than 0.05 indicate the regression is statistically significant. Please note that although HSI and r^2 values range between 0.0 and 1.0, they are not related measurements.

The initial regression analysis involved HSI values derived from the mean of environmental observations over the entire study period. The effects of a limited sampling program upon the model output were assessed by partitioning the environmental data set into seasons of 3 months duration. The seasons were Sum84 (Jun., Jul., Aug. 1984), Fall85 (Sept., Oct., Nov. 1984), Win84 (Dec. 1984, Jan., Feb. 1985), Spr85 (Mar., Apr., May 1985) and Sum 85 (June., Jul., Aug. 1985). Environmental data from each of these periods were used to derive HSI values which were regressed against the growth rates calculated over the entire study period at each site.

4.2 Results

4.2.1 Oyster Growth

Growth in shell height for both year classes followed the general seasonal pattern of high growth rates in the summer of 1984 which gradually tapered off during fall to no growth during the winter months. Growth rates began to increase again in February-March 1985 and continued to rise into the summer months.

Shell height growth was highly variable between sites for both year classes. Final mean sizes in August 1985 for Year 0 oysters ranged from 100 mm at Okeover Inlet to 57 mm at West Vancouver (Figure 4). The net which held Year 0 oysters at Keats Island was lost 3 months into the study due to a storm. For Year 1 oysters, mean shell height at the termination of the study ranged from 108 mm at Okeover Inlet to 70 mm at West Vancouver (Figure 5). From an analysis of the polynomials fitted to the growth

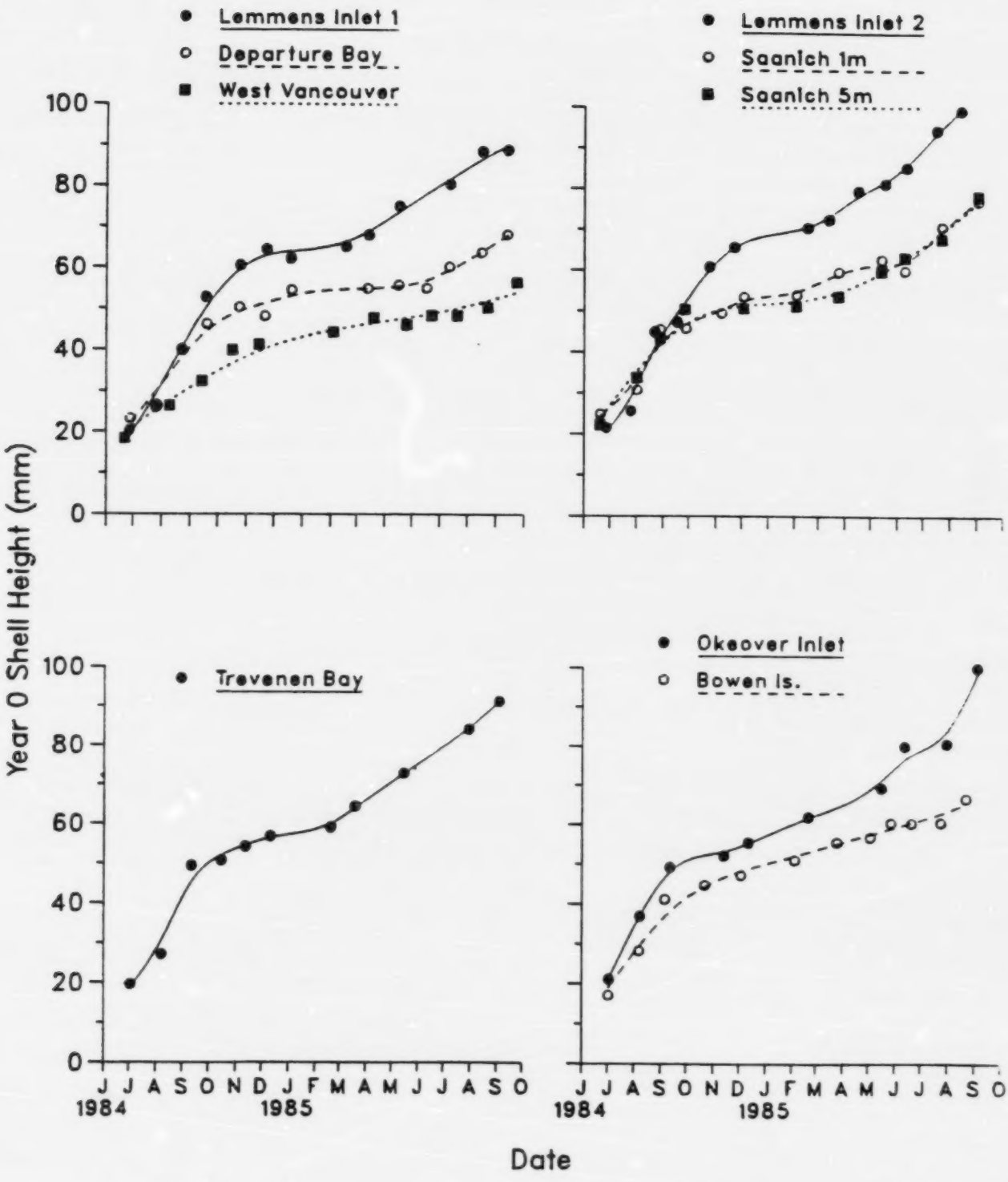


Figure 4. Increase in shell height (umbo to maximum distance) of Year 0 oysters over time.

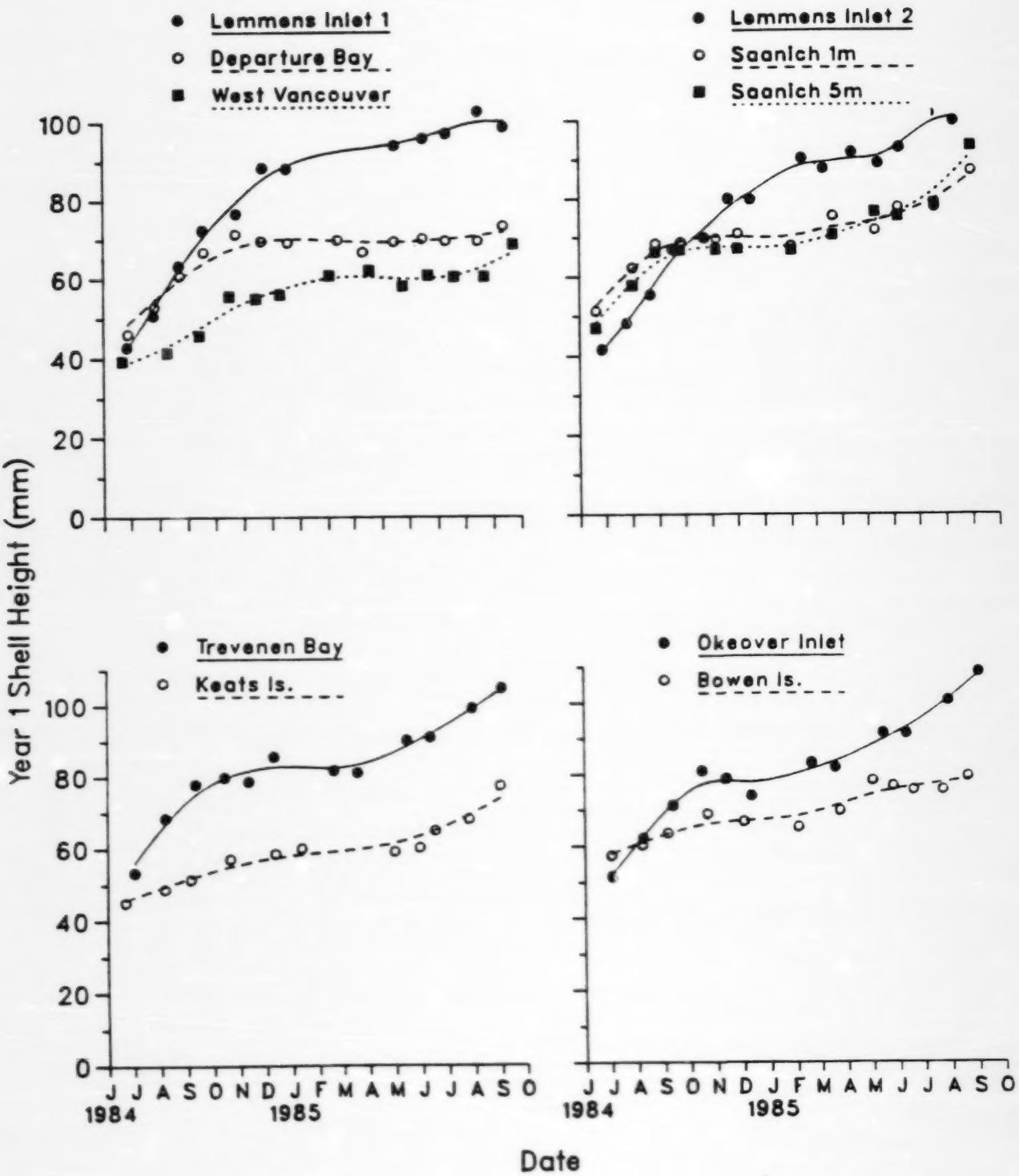


Figure 5. Increase in shell height (umbo to maximum distance) of Year 1 oysters over time.

data, the 10 sites were categorized into three groups (Brown 1986, Brown and Hartwick, In Press b). The high growth group consisted of Trevenen Bay, Okeover Inlet, and Lemmens Inlet 1 and 2. The growth at Departure Bay, Bowen Island, and Saanich 1 m and 5 m was significantly less than that observed at the above four sites and comprised the medium growth group. The final group consisted of Keats Island (Year 1 only) and West Vancouver, which had the lowest shell height growth.

4.2.2 Survival and Production

Percent survival calculated over the entire study (14 months) was lower for Year 0 compared to Year 1 oysters at each site (Figure 6). For both year classes, most mortalities occurred during the initial 2 months of the study (July-August 1984). Few mortalities were observed in subsequent months, except for Bowen Island, where mortalities occurred throughout the study. Survival rate of Year 1 oysters varied little between sites and ranged from 80.5-89.7% with the exception of lower survival at Bowen Island (63.2%). For Year 0 oysters, survival rates at Bowen Island, Departure Bay, and Saanich 1 m and 5 m were considerably lower (31.5-43.5%) than rates for the remaining sites (48.8-57.3%). Despite the low growth rates at Keats Island and West Vancouver, mortality rates of oysters at these sites did not differ from that of oysters at the high growth sites.

Production figures largely followed the observed trends in shell height (Figure 7). For a given site, Year 1 oyster production (0.48-1.82 g/100 oysters/day) was higher than that of Year 0 oysters (0.14-0.87 g/100 oysters/day).

4.3 Model Validation

Environmental factors which showed the greatest variations between sites were salinity, chlorophyll concentrations, TPM, and density of fouling organisms. Water temperature fluctuated seasonally but differed little between sites at any given time of the year. Phytoplankton biomass and salinity also had significant seasonal variation.

Environmental and growth data used to test the model are summarized in Table 4. For a particular environmental variable, the annual mean was calculated from monthly averages of duplicate or triplicate samples, excluding data collected in December, January and February. Low water temperatures and near absence of phytoplankton biomass during these months resulted in seasonal Win 84 HSI values which were uniformly low and did not distinguish between sites.

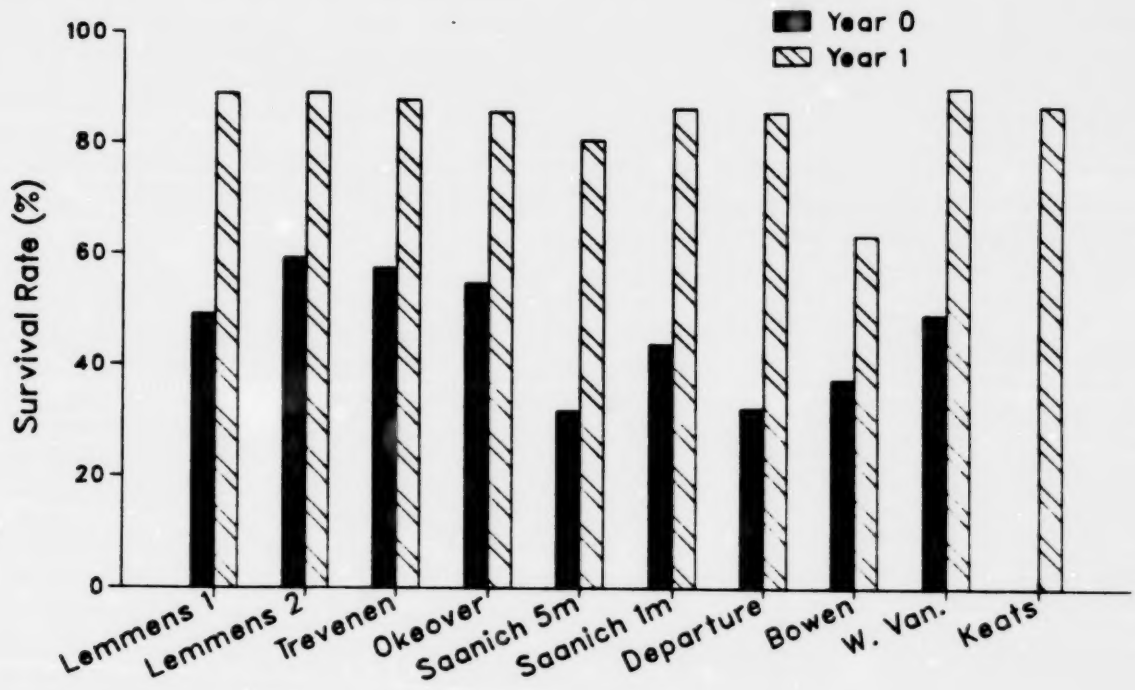


Fig. 6. Survival rates over 14 months for both age classes.

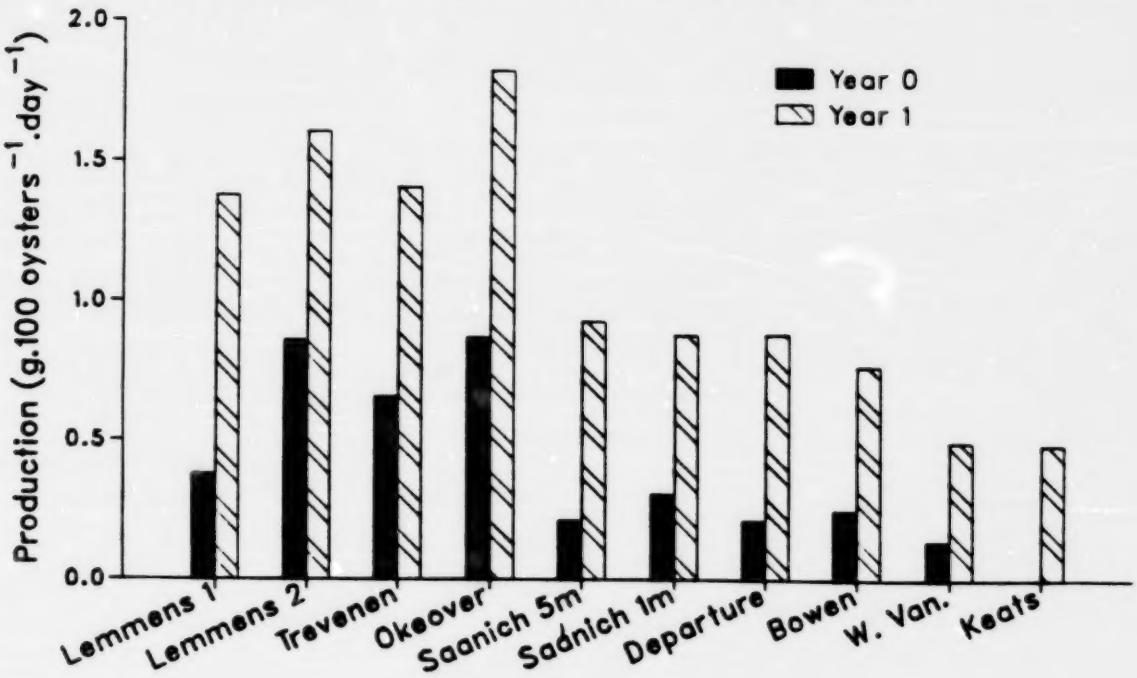


Fig. 7. Dry meat weight production over 14 months.

Table 4. Means of environmental variables over entire study period and derived Suitability Index (SI) and Habitat Suitability Index (HSI) values. Means (n=11) were calculated from monthly averages of multiple (n = 2 or 3) samples taken from June 1984 to August 1985 excluding December 1984 to February 1985. HSI values are representative of overall site suitability for 14 mo.
Chl. *a* = chlorophyll *a*; PIM = particulate inorganic matter.

Site	Temperature (°C)	SITEMP	Salinity (ppt)	SISAL	Chl. *a* ($\mu g \cdot l^{-1}$)	SIFOOD	PIM ($mg \cdot l^{-1}$)	SIPIM	SI Fouling	HSI
Lemmens Inlet 1	14.7	0.96	24.9	1.00	8.56	0.69	6.2	0.97	0.75	0.77
Lemmens Inlet 2	14.7	0.96	25.2	1.00	10.51	0.87	6.3	0.97	1.00	0.95
Trevenen Bay	13.0	0.72	24.5	1.00	6.86	0.53	8.5	0.96	1.00	0.79
Okeover Inlet	14.6	0.94	24.4	1.00	5.25	0.39	9.2	0.96	1.00	0.78
Departure Bay	14.5	0.93	23.2	1.00	4.03	0.28	1.3	1.00	0.50	0.50
Saanich 1m	14.0	0.86	25.9	1.00	3.59	0.24	10.6	0.95	0.50	0.58
Saanich 5m	13.0	0.72	26.3	1.00	4.34	0.30	10.1	0.95	1.00	0.68
Bowen Is.	14.4	0.92	17.3	0.66	6.95	0.54	1.7	1.00	0.25	0.41
Keats Is.	14.6	0.94	14.3	0.51	4.69	0.34	1.6	1.00	0.25	0.37
West Vancouver	13.9	0.84	18.4	0.72	10.72	0.88	2.5	0.99	0.25	0.46

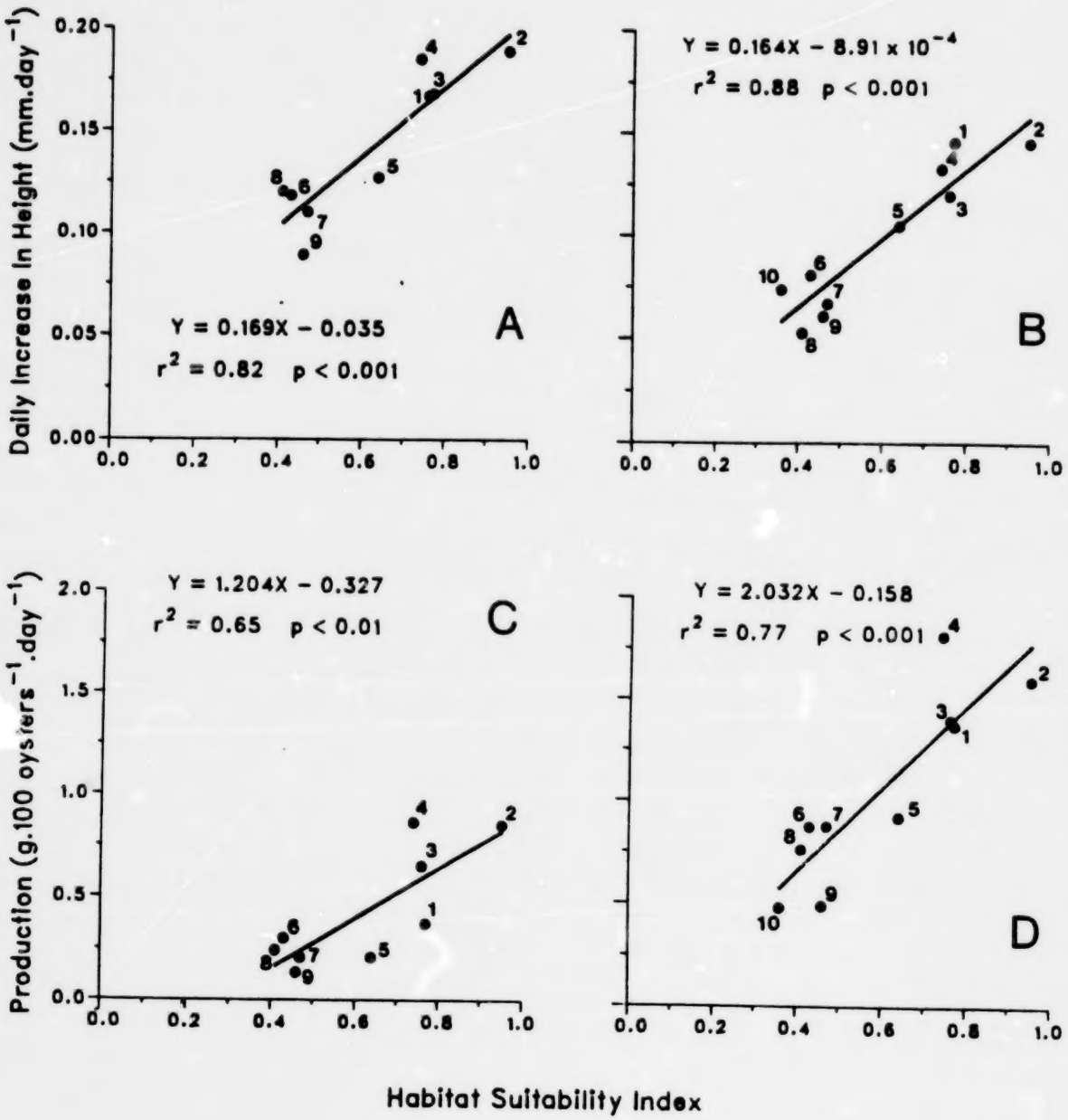

Daily Increase in Height (mm.day^{-1})
Y = 0.169X - 0.035
r^2 = 0.82 p < 0.001
A
Y = 0.164X - 8.91 x 10^{-4}
r^2 = 0.88 p < 0.001
B
Production (g.100 oysters^{-1}.day^{-1})
Y = 1.204X - 0.327
r^2 = 0.65 p < 0.01
C
Y = 2.032X - 0.158
r^2 = 0.77 p < 0.001
D
Habitat Suitability Index

Figure 8. Habitat Suitability Index, (HSI) values derived from environmental data for the entire study regressed against: A. Shell growth of Year 0 oysters; B. Shell growth of Year 1 oysters; C. Dry meat weight production of Year 0 oysters; and D. Dry meat weight production of Year 1 oysters. Sites are coded as: 1 = Lemmens Inlet 1; 2 = Lemmens Inlet 2; 3 = Trevenen Bay; 4 = Okeover Inlet; 5 = Saanich 5 m; 6 = Saanich 1 m; 7 = Departure Bay; 8 = Bowen Island; 9= West Vancouver; 10 = Keats Island.

Table 5. Coefficients of determination (r^2) for regressions of mean daily shell height increase ($mm \cdot day^{-1}$) between June 1984 and August 1985 of Year 0 and Year 1 oysters against site-specific HSI values calculated from entire study environmental data and seasonal (3 mo) and selected monthly data subsets. For comparison, available food was determined from: 1) chlorophyll *a* (chl. *a*) and; 2) particulate organic matter (POM).

Available Food	Entire Study	Sum 84	Aug 84	Sept 84	Fall 84	Spr 85	Sum 85
Year 0							
Chl. *a*	0.83 ***	0.29 ns	0.53 **	0.53 *	0.39 *	0.85 ***	0.04 ns
POM[a]	-	-	0.31 ns[b]	0.90 ***[c]	0.92 ***[b]	0.60 **	0.36 *
Year 1							
Chl. *a*	0.88 ***	0.46 **	0.67 ***	0.55 *	0.39 *	0.72 ***	0.02 ns
POM[a]	-	-	0.17 ns[b]	0.66 **[c]	0.77 **[b]	0.56 **	0.39 *

* $P \leq 0.05$: ** $P \leq 0.01$; *** $P \leq 0.001$; ns not significant.
Except when noted, $n = 9$ for Year 0 and $n = 10$ for Year 1, where n is the number of sites.

a POM data was not collected during June - July 1984.

b Sites are Lemmens 1 & 2, Departure Bay, Keats Island, Bowen Island

c Sites are Lemmens 1 & 2, Saanich 1 m & 5 m, Departure Bay, West Vancouver

Winter data decreased the power of the HSI model to distinguish between the ability of sites to grow oysters over the potential growing season in British Columbia. At all sites, levels of dissolved oxygen, pH, disease and predation were not harmful to oysters, thus the variables were given an SI value of 1.0. Water movement was assigned a SI value for 1.0 for testing the model.

Regressions of HSI values (based upon complete study environmental data) against oyster growth were found to be highly significant for both Year 0 ($r^2 = 0.83$, $p \leq 0.001$) and Year 1 ($r^2 = 0.88$, $p \leq 0.001$) oysters (Figure 8). There were also significant correlations between HSI values and production for Year 0 ($r^2 = 0.69$, $p \leq 0.001$) and Year 1 ($r^2 = 0.81$, $p \leq 0.001$) oysters.

Fluctuations in phytoplankton biomass strongly affected the capability of the model when data from the 3 month seasonal periods were used as input. The correlations between seasonal HSI values and growth of Year 0 and Year 1 oysters are summarized in Table 5 respectively. The patterns of correlations were similar for both year classes. Correlations between HSI values and shell growth were highest when the input data were collected in August 1984 and Spr85 (March-May). For the Spr85 data, chlorophyll *a* concentration was a better estimate of available food than POM. For September and Fall 1984, HSI ratings based on POM resulted in better correlations than those derived from phytoplankton pigment data. Data from Sum84 generally resulted in low, or non-significant correlations and zero HSI values occurred for all sites when only Win84 data were used as input.

While the correlation between HSI ratings derived from Spr85 and oyster growth was highly significant, the HSI values were slightly lower than those calculated from the entire study data. Spring and fall water temperatures were lower than annual mean temperatures which resulted in lower Spr85 and Fall84 HSI values for all sites.

5. USING THE MODEL

Given the task of identifying the most suitable site for oyster culture among several potential areas, the model user should begin by researching existing data-bases. From discussions with government agencies and regional offices, some sites may be eliminated because of low economic suitability and the potential of conflict with other coastal developments.

Initial estimates of the values of some CSI variables can be made prior to conducting a field survey. Hydrographic charts allow estimation of water depth, area available for culture, tidal currents

and wave exposure. Topographic and regional planning maps show road access, power, local industries, municipal sewage outfalls, and freshwater sources. The Atmospheric Environment Service of Environment Canada publishes annual records on prevailing winds and climatic conditions (Environment Canada 1981). Oceanographic information for several coastal areas has been gathered by the Department of Fisheries and Oceans and the Department of Oceanography at the University of British Columbia, although site-specific information on small bays is often absent, particularly about phytoplankton populations.

Field surveys should initially emphasize the economic and physical characteristics of the sites. The area available for culture should be accurately assessed in relation to water depth, substrate composition, intertidal area usable for handling of shell-stock, tidal flow and wave exposure. After the initial survey, the remaining candidate sites should be priorized for intensive investigations, which may include measurements of water temperature, salinity, available food, suspended sediments and dissolved oxygen, predator abundance and seasonal occurrence and severity of fouling organisms. When evaluating several sites with incomplete data sets, the CSI model can be used as a means of comparison provided the unknown variables are assigned a constant value. It is important that such assumptions be explicit when comparing CSI ratings. During growing seasons (typically March-November), the variation in the values of these environmental factors can be large, thus multiple measurements need to be taken. A good survey should collect adequate data (at least monthly) to document the annual cycle of phytoplankton abundance (an important factor to good performance of the model), fresh water influxes and water temperatures. Phytoplankton biomass and fresh-water run-off are low during winter months, thus only one or two visits are needed to assess minimum winter water temperatures. In coastal areas within the latitudinal range covered by the field study, waters with salinity above 20 ppt will rarely have temperatures lower than 5-6°C below 1 m.

Sampling methodology should be consistent between sites and visits. For off-bottom culture, samples should be taken in the vicinity of the proposed longlines at a depth equivalent to the mid-point of suspended oysters. For on-bottom culture, samples should be taken at high slack tide about 1 m above the substrate. Variation in phytoplankton abundance over a tidal cycle should be noted during the phytoplankton bloom. One strategy would be to sample at slack, ebb and flood stages of the tidal cycle. Proper sampling and analytical techniques should be employed. Appendix A discusses data collection and the relevant references should be consulted for a more detailed description of the analytical techniques.

The final selection of a site is a partially subjective process based upon both economic and biophysical factors; however, if values of any of the three major indices (Economic, Habitat or Culture) are

less than 0.50, significant economic or production problems are likely to be encountered. To reach a sound decision, the grower should weigh the results of the model with the experienced opinions of culture biologists and oyster growers. After the aquaculture operation has been established, a regular water monitoring program can assist in evaluating the productivity of the lease and planning further developments such as the remote setting of oyster larvae. In addition, potential environmental impacts from other coastal developments or other shellfish or finfish culture operations can be detected at an early stage.

It is apparent that the selection of an aquaculture site and the subsequent monitoring of water quality can be an expensive and time consuming process. The effort expended on these activities must be balanced against the consequences of an aquaculture operation encountering difficulties as a result of unknown or unconsidered characteristics of the site.

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APPENDIX A: MEASUREMENT OF HABITAT SUITABILITY VARIABLES

V_1 Water Temperature

Surface water temperature can be economically measured with a mercury thermometer which covers the range of -2 to 30 °C. A variety of electronic temperature meters exist, some of which also measure salinity, conductivity, pH and/or dissolved oxygen. If the sensor or probe is at the end of a long cable, the thermal profile of the water column can be determined. Another way to measure water temperature at depth is to bring a sample of water to the surface in a commercial sampling bottle (such as Niskin or Van Donn bottles), or in a pop bottle attached to a weighted line which can be uncorked and filled at depth via a second string to the surface attached to the cork.

V_2 Available Food

The amount of available food is one of the most important variables affecting oyster growth. In the model, available food is defined as phytoplankton biomass determined either from concentration of chlorophyll *a* pigments or weight of particulate organic matter (POM). Since phytoplankton contain chlorophyll *a* pigments for photosynthesis, the presence of this molecule should be proportional to the biomass of phytoplankton, although concentrations can vary slightly depending on species and environment conditions.

The simplest and most applicable technique to oyster growers for estimating chlorophyll concentration is the measurement of water transparency using a secchi disc. The secchi disc is usually 30 cm in diameter and painted a flat white with a rope marked off in metres attached to its centre. The observer lowers the secchi disc over the shady side of the boat and records the depth at which it just disappears from sight.

The relationship between secchi disc depth and chlorophyll *a* concentration is not linear but logarithmic or downward curvilinear. This is largely due to the rapid attenuation or absorption of light by sea water and various suspended particles. From secchi disc depths and chlorophyll *a* concentrations collected during the field study (236 observations), similar data on freshwater lakes (Carlson 1977), and experience with blue mussel culture in Newfoundland (Sutterlin *et al.* 1981) conversion factors for secchi depth to available food SI values can be suggested.

Very shallow secchi disk readings (0-3 m) would indicate chlorophyll *a* concentrations greater than 8.0 µg/l which convert to SI values ranging between 0.70 and 1.0. In the secchi depth range of 3-5 m, chlorophyll *a* concentrations would be between 2.0 - 8.0 g/l with SI values between 0.3 and 0.7. Below 2.0 µg/l, food is limiting although water currents could improve the number of

particles coming in contact with the oyster. Secchi disc depths greater than 8 m generally indicate very low chlorophyll concentrations, hence SI values would range from 0.0 to 0.3. Secchi disk readings greater than 8 m are common in most B.C. coastal inlets during winter months. The observer should also note the colour of the secchi disk just before it disappears. A dark green to gold brown would indicate that phytoplankton are the principal factor in light absorption while dark brown or light grey colour could be the result of high concentrations of suspended sediments. If suspended sediments appear to be in significant concentrations, then estimates of available food should be reduced and the negative effects of heavy silt loadings should be considered (see V_5 suspended sediments).

While simple to use, the secchi disc is not the most accurate method of assessing phytoplankton biomass and it should only be considered as an approximate estimate. One problem with the secchi disc is the extent to which phytoplankton affects water transparency as opposed to other suspended particles can not be determined. The amount of direct sunlight and surface wave action will also affect the depth to which the secchi disc is visible. Large farms concerned about the nutrition of adult oysters and remotely set larvae should consider the benefit of obtaining more precise estimates of available food. We recommend the determination of chlorophyll *a* pigments following the technique of Strickland and Parsons (1982). Water samples are collected with a water sampling bottle and passed through a 300 μm mesh to remove zooplankton and large debris. The screened sample (0.5 - 1.0 l) is filtered in the field through a 47 mm dia Millipore® AA filter. Approximately 1-2 ml of 1 % $MgCO_3$ solution are added to the final 100 ml of sample to inhibit the decomposition of the chlorophyll molecules. Filters are immediately frozen in darkness and stored for no more than 1 week before analysis. Chlorophyll pigments are extracted by dissolving the filters in 90% acetone solution for 18-20 h at 4°C. Extinction coefficients of the aliquot are determined by a spectrophotometer (the major equipment cost) and the concentration of chlorophyll *a* (μg/l) is calculated using the equations of Parsons and Strickland (Strickland and Parsons 1982).

For total particulate matter (seston) analysis, the weights of organic and inorganic particles suspended in the water column are determined after filtration. Since phytoplankton can form a large component of the particulate organic matter, the analysis can provide another estimate of available food. From the field study, secchi disc data was found to be less suitable for model input than particulate organic matter. The major cost is an analytical balance, accurate to 0.001 g, which is commonly found in many research and educational laboratories. The description here follows Strickland and Parsons (1982) or Parsons *et al*. (1984) with a few modifications.

Samples (0.5-1.0 l) for weight determination of seston are filtered in the field through pre-weighed GF/C Whatman glass microfiber filters, previously ashed for 2 h at 450°C. After the sample passes through, the filter is rinsed with 2-3 ml of distilled water or 10 ml of isotonic ammonium formate. Suction is applied until the filter is dry, then it is removed and immediately frozen in the dark. Analysis should occur within 2 wk of collection. Weight of TPM (mg/l) is determined after drying the filter at 60°C for 12 h. Weights of particulate organic matter (POM) and particulate inorganic matter (PIM) were determined from weight loss and weight of residue, respectively, after ignition at 450°C for 5 h minimum. The model variable suspended sediments (V_5) is most accurately estimated from the concentraton of PIM.

V_3 Substrate Composition (On-bottom culture only)

Substrate composition of a beach can be determined fairly readily by simply noting the extent of occurrence of soft mud, firm sediment and rocky areas, and the relative proportions of various particle sizes such as silt, sand, gravel, cobble and boulders.

V_4 Intertidal Exposure (On-bottom culture only)

When evaluating an on-bottom site, the grower must consider the size of the area between the recommended tide levels for oyster culture. This is easily done by measuring with a tape-measure or by pacing, and using tide predictions for the area.

V_5 Suspended Sediments

As mentioned in the section pertaining to available food (V_2), inorganic seston or PIM provides a good estimate of suspended sediments. The inorganic fraction of the total seston is determined from the weight of particles remaining on a glass fiber filter after combustion at a high temperature (450°C for 5 hrs.).

A less precise estimate of this variable is to note the colour of the secchi disc as it is lowered into the water. If the colour ranges from brown to gray then sediments are probably the major cause of the reduction in water transparency. The secchi disc observation is qualitative, because the ratio of organic to inorganic particles can not be determined.

In the areas studied for field validation of the model, concentrations of suspended sediments rarely rose above 14.0 mg/l which would have little effect upon oyster production. In coastal areas, other than estuaries, suspended sediments do not seem to be a limiting factor for oyster culture. In estuaries, volumes of sediment carried by freshwater run-off or river discharges may be in high enough concentrations to be harmful to oysters.

V_6 Water Movement

Two types of water motion must be considered, waves and currents. The direction that the opening of the bay is facing should be determined and the distance that wind travels across the water measured directly or from a hydrographic chart. From data published by the Atmospheric Environment Service of Environment Canada (Environment Canada, 1981), seasonal wind speeds and directions may be obtained for certain coastal areas. Wave height and periodicity may be estimated from Figure 7.8 in Thomson (1981), given wind speed, duration and fetch. Observing beach areas nearby can provide a good means of determining wave exposure. Soft sediments occur in areas of little wave action; while boulder and cobble beaches sometimes indicate heavy wave action. The higher that logs are distributed above the high tide line and into the bush, the greater the wave action. Existing shell stock washed into piles around the high tide line, is another indicator of strong wave action.

Current speeds can be easily determined by timing the distance travelled in water by an object such as an orange. Measurements should be made at during spring and neap tides, at high, mid, and low water.

V_7 Fouling Organisms

Fouling organisms are assessed qualitatively from densities of mussels (Mytilus edulis) and barnacles (Balanus glandula) and other epibiota such as tunicates and various seaweeds on the shells of oysters or other substrates. If little oyster shell is visible, then the fouling is heavy (SI = 0.25). Moderate fouling is defined as at least half of the oyster covered (SI = 0.50). If only occasional fouling organisms are present, then the rating is light (SI = 0.75 or 1.0).

V_8 Predation

Although the impact of seastars Pisaster ochraceus and Pycnopodia helianthoides, the most common predator of oysters, can be reduced through diligent maintenance, dense populations of adult seastars and heavy sets of juveniles are considered a negative factor which should be subjectively taken into account when assessing a site. Management agencies should be contacted about the occurrence of Japanese oyster drills (Oceanebra japonica).

V_9 Disease

Inquiries should be made to local oyster growers, oyster growers' associations, and management agencies regarding the past history of disease occurrence in the areas near the site under evaluation.

V_{10} Salinity

Salinity can be measured wth either hydrometer, refractrometer or electronic meter. An electronic meter must be regularly serviced and calibrated to maintain accuracy.

Elevated freshwater flow during the spring can often depress surface salinity in coastal inlets. While these low salinities may be of consequence to bottom cultured oysters, the freshwater layer usually does not extend deep enough to affect off-bottom cultured oysters. The extent of freshwater influx is dependent upon a number of factors including, volume of freshwater inflow and its duration, surface area and depth of the basin, and volume of exchange between the basin and outside waters.

From the field study, it was observed that a considerable influx of freshwater was required before salinity was reduced deeper than one meter. The sites with poor growth rates and low salinity were located in Howe Sound which is strongly affected by the Fraser and Squamish Rivers. In contrast, salinity remained consistently high in Lemmens Inlet even during the period of spring run-off, because no large rivers occur there.

V_{11} Dissolved Oxygen

Dissolved oxygen may be determined by either an oxygen meter or Winkler titration procedure. The amount of dissolved oxygen in seawater at 100% oxygen saturation is dependent upon both temperature and salinity. Cold, highly saline waters hold more oxygen than warm, less saline waters. Saturation levels lower than 70% will rarely occur in marine coastal areas which have moderate water circulation. In deep, undisturbed basins, low oxygen levels can occur below the thermocline during late summer. When the thermocline disappears in the fall, oxygen levels are renewed by sinking surface waters. Levels of dissolved oxygen also fluctuate seasonally with water temperature and phytoplankton biomass. At the study sites, however, oxygen saturation was generally above 80 % throughout the year. In areas with little urban or industrial development, SI (Dissolved Oxygen) should be assigned a value of 1.0. Dissolved oxygen levels are more of concern to fish farmers since salmonids have a greater sensitivity to low oxygen levels compared to oysters.

V_{12} pH

In coastal waters, pH conditions stressful to the oyster will rarely occur. For unexploited coastal areas, SI (pH) values should be assigned 1.0. It was included in the model because certain industrial waste products can affect the pH levels of enclosed waters. Furthermore pH levels should be monitored in enclosed hatchery systems.

There are a variety of electronic pH meters available, some of which are field portable. Strickland and Parsons has a discussion on the calibration and use of pH meters for seawater analysis.

APPENDIX B: EXAMPLE OF USE OF TABLES 1, 2 AND 3 FOR CALCULATION OF ECONOMIC, HABITAT AND CULTURE SUITABILITY INDEXES, PLUS ADDITIONAL WORKING COPIES OF EACH TABLE.

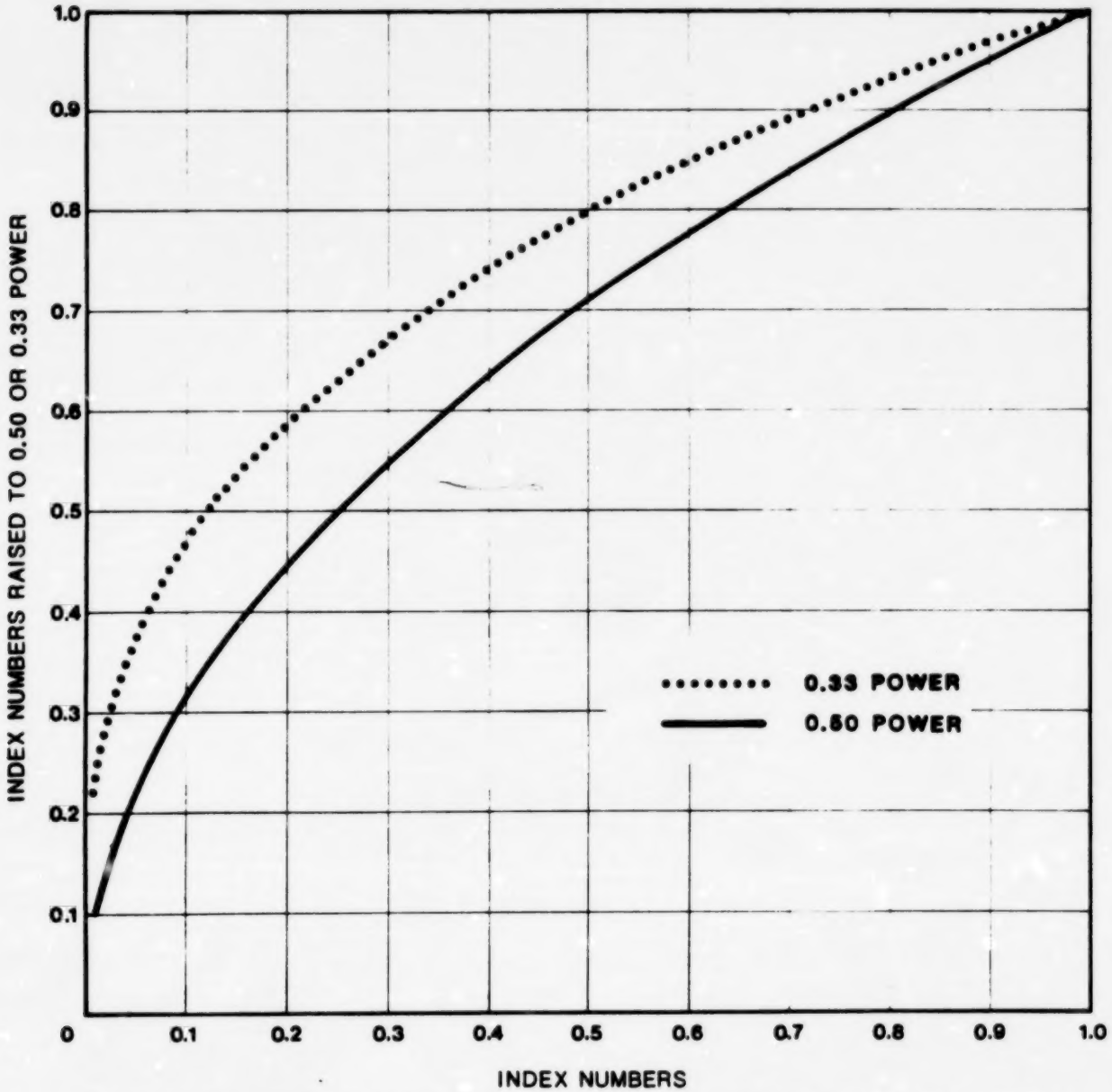

Figure 9. Graph of index numbers between 0.01 and 1.00 raised to the 0.05 and 0.33 powers for use in calculation of Economic, Habitat and Culture Suitability indexes.

Example of use of Economic Index Worksheet equations and worksheet.

Variable	Index Value	Comments
E_1 (Theft)	0.7	- nearby park and boat launch cause concern
E_2 (Recreational Conflicts)	0.7	- although about 1 mile from park, some people may stray onto lease
E_3 (Clam Harvesting)	0.3	- part of lease applied for is regularly dug
E_4 (Navigation Conflicts)	0.8	- intertidal stake culture may interfere with recreational boating at some tides
E_5 (Pollution)	1.0	- no recorded coliform closures, no industry nearby
E_6 (Riparian Rights)	0.8	- two upland owners must consent to any planned stake culture
E_7 (Distance)	0.9	- boat launch and labor supply, etc. nearby
E_8 (Surveillance)	0.7	- leasee lives across inlet, and to some degree monitor activity on lease
E_9 (PSP)	0.8	- 2-3 month long closures occur about once in three years

Steps to Calculate Economic Suitability Index (ESI)

1. EIC (Human Activity) =

$$[(E_1 \times E_2 \times E_3)^{0.33} \times (E_4 \times E_5 \times E_6)^{0.33}]^{0.50}$$

$$[(0.7 \times 0.7 \times 0.3)^{0.33} \times (0.8 \times 1.0 \times 0.8)^{0.33}]^{0.50} = 0.7 \text{ *culture for on-bottom}$$

or

$$[(E_1 \times E_2)^{0.50} \times (E_4 \times E_5 \times E_6)^{0.33}]^{0.50}$$

$$[(\_\_ \times \_\_)^{0.50} \times (\_\_ \times \_\_ \times \_\_)^{0.33}]^{0.50} = \_\_\_\_\_ \text{* for off-bottom culture}$$

2. EI (Access) = $(E_7 \times E_8)^{0.50}$

$$= (0.9 \times 0.7)^{0.50} = 0.8 \text{ *}$$

3. EI (PSP) = E_9 = 0.8

4. Economic Suitability Index = ESI =

[EI (Human Activity) x EI (access) x EI(PSP)]$^{0.33}$ =

$$[\underline{\ 0.7\ } \times \underline{\ 0.8\ } \times \underline{\ 0.8\ }]^{0.33} = \underline{\underline{0.77}}^{*}$$

*To solve an equation such as $(E_1 \times E_2 \times E_3)^{0.33}$, simply multiply the three values together and take the $^{0.33}$ power or cube root of the product; for example:

$$(.4 \times .7 \times .6)^{0.33} = (0.168)^{0.33} = \underline{0.56}$$

The product of the three numbers (0.168) taken to the 0.33 power (0.56) can be read from Figure 9 in Appendix B.

Example use of Life Requisite Suitability Index (LRSI) and Habitat Suitability Index (HSI) worksheet and equations.

Variable	Index Value	Data and Comments
V_1 (Temperature)	1.0	- monthly records of water temperature are over 14°C from May-September
V_2 (Available Food)	0.75	- secchi disc readings less than 4 m occur for 6 months in spring and summer. Wild oysters plump in spring.
V_3 (Substrate)	0.75	- substrate somewhat silty over about half of beach (therefore, okay for stake culture), rest is firm bottom
V_4 (Intertidal Exposure)	1.0	- good, about 1/2 hectare of beach between 0.5 and 2 m tide levels
V_5 (Suspended Sediments)	1.0	- no river run-off; water color never milky-grey
V_6 (Water Movement)	0.8	- bay is protected, therefore little wave activity; would prefer faster currents however.
V_7 (Disease)	1.0	- talks with government officials indicate no records of disease in area
V_8 (Fouling Organisms)	0.6	- heavy barnacle sets may make seed survival poor, however, there is adequate high ground for seed rearing where barnicles can be avoided; some cleaning may be required to market half-shell oysters
V_9 (Predators)	0.8	- very few seastars seen
V_{10} (Salinity)	1.0	- not influenced by any major source of fresh water
V_{11} (Oxygen)	1.0	)
V_{12} (pH)	1.0	) no reason to suspect any problem

Steps to Calculate Habitat Suitability Index (HSI)

1. LRSI (Growth) = $(V_1 \times V_2)^{0.50}$ = $(\underline{1.0} \times \underline{0.75})^{0.50}$ = $\underline{0.87}$*

   *For on-bottom culture only, LRSI (Growth) = the lesser of $(V_1 \times V_2)^{0.50}$ or V_3, or V_4

2. LRSI (Survival) = the lesser of V_5, V_6, V_7, V_8, or V_9 = $\underline{0.6}$. This is because all are considered to affect survival in a major way and poor values of one or more cannot be compensated in any way by high values of other variables.

3. LRSI (Water chemistry) = the lesser of V_{10}, V_{11}, or V_{12} = $\underline{1.0}$. Again, a poor value for one variable is detrimental to culture.

4. Habitat Suitability Index = HSI =

   [LRSI (Growth) x LRSI (Survival)]$^{0.50}$ = $\underline{\underline{0.72}}$ *, if LRSI (Water Chemistry) is greater than or equal to 0.70. If it is less than 0.70 then the HSI = [[LRSI (Growth) x LRSI (Water Chemistry)]$^{0.50}$ x LRSI (Survival)]$^{0.50}$ = $\underline{\underline{\quad}}$*

*Note: See Figure 9 (Appendix B) for values of numbers taken to the 0.50 power

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Example use of Culture Suitability Index equations and worksheet.

Culture suitability Index = CSI =

(ESI x HSI)$^{0.50}$ =

($\underline{.77}$ x $\underline{.72}$)$^{0.50}$ = $\underline{\underline{0.74}}$*

Where ESI is the value for the overall Economic Suitability Index and HSI is the value for the overall Habitat Suitability Index.

*Note: See Figure 9 (Appendix B) for values of numbers taken to the 0.50 power.

Table 1: Economic Index equations and worksheet. See Appendix B for example of use.

Variable	Index Value	Comments
E_1 (Theft)	_____	
E_2 (Recreational Conflicts)	_____	
E_3 (Clam Harvesting)	_____	
E_4 (Navigation Conflicts)	_____	
E_5 (Pollution)	_____	
E_6 (Riparian Rights)	_____	
E_7 (Distance)	_____	
E_8 (Surveillance)	_____	
E_9 (PSP)	_____	

Steps to Calculate Economic Suitability Index (ESI)

1. EI (Human Activity) =

   $[(E_1 \times E_2 \times E_3)^{0.33} \times (E_4 \times E_5 \times E_6)^{0.33}]^{0.50}$

   $[(\_\_ \times \_\_ \times \_\_)^{0.33} \times (\_\_ \times \_\_ \times \_\_)^{0.33}]^{0.50}$ = _____* for on-bottom culture or

   $[(E_1 \times E_2)^{0.50} \times (E_4 \times E_5 \times E_6)^{0.33}]^{0.50}$

   $[(\_\_ \times \_\_)^{0.50} \times (\_\_ \times \_\_ \times \_\_)^{0.33}]^{0.50}$ = _____* for off-bottom culture

2. EI (Access) = $(E_7 \times E_8)^{0.50}$

   = $(\_\_ \times \_\_)^{0.50}$ = _____*

3. EI (PSP) = E_9 = _____

4. Economic Suitability Index = ESI =

[EI (Human Activity) x EI (access) x EI(PSP)]$^{0.33}$ =

[_____ x _____ x _____]$^{0.33}$ = _____*

*To solve an equation such as $(E_1 \times E_2 \times E_3)^{0.33}$, simply multiply the three values together and take the $^{0.33}$ power or cube root of the product; for example:

$(.4 \times .7 \times .6)^{0.33} = (0.168)^{0.33} = \underline{0.56}$

The product of the three numbers (0.168) taken to the 0.33 power (0.56) can be read from Figure 9 in Appendix B.

Table 2. Life Requisite Suitability Index (LRSI) and Habitat Suitability Index (HSI) worksheet and equations. See Appendix B for example of use.

Variable	Index Value	Data and Comments
V_1 (Temperature)	_____	
V_2 (Available Food)	_____	
V_3 (Substrate)	_____	
V_4 (Intertidal Exposure)	_____	
V_5 (Suspended Sediments)	_____	
V_6 (Water Movement)	_____	
V_7 (Disease)	_____	
V_8 (Fouling Organisms)	_____	
V_9 (Predators)	_____	
V_{10} (Salinity)	_____	
V_{11} (Oxygen)	_____	
V_{12} (pH)	_____	

Steps to Calculate Habitat Suitability Index (HSI)

1. LRSI (Growth) = $(V_1 \times V_2)^{0.50}$ = (__ x __)$^{0.50}$ = ____*

   *For on-bottom culture only, LRSI (Growth) = the lesser of $(V_1 \times V_2)^{0.50}$ or V_3, or V_4

2. LRSI (Survival) = the lesser of V_5, V_6, V_7, V_8, or V_9 = ____. This is because all are considered to affect survival in a major way and poor values of one or more cannot be compensated in any way by high values of other variables.

3. LRSI (Water chemistry) = the lesser of V_{10}, V_{11}, or V_{12} = ____. Again, a poor value for one variable is detrimental to culture.

4. Habitat Suitability Index = HSI =

   [LRSI (Growth) x LRSI (Survival)]$^{0.50}$ = _____*, if LRSI (Water Chemistry) is greater than or equal to 0.70. If it is less than 0.70 then the HSI = [[LRSI (Growth) x LRSI (Water Chemistry)]$^{0.50}$ x LRSI (Survival)]$^{0.50}$ = _____*

*Note: See Figure 9 (Appendix B) for values of numbers taken to the 0.50 power.

TABLE 3 Culture Suitability Index equations and worksheet. See Appendix B for example of use.

Culture Suitability index = SCI =

$(ESI \times HSI)^{0.50}$ =

$(\frac{\quad}{\quad} \times \frac{\quad}{\quad})^{0.50}$ = _____*

Where ESI is the vlaue for the overall Economic Suitability Index and HSI is the value for the overall Habitat Suitability Index

*Note: See Figure 9 (Appendix B) for values of numbers taken to the 0.50 power.